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SUMMARY OF TALK

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# DESIGN CONSIDERATIONS IN RADIATION HARDENING OF TELEMETRY AND CONTROL CIRCUITRY IN SPACECRAFT

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In October 1962 Explorer XV was launched in an orbit to map the newly created artificial radiation belt. Successful integration and launch of this spacecraft was the results of doing a "rush job" modification on flight spare hardware which was originally designed for Explorer XII and XIV, two GSFC satellites placed in highly eliptical orbits for energetic particle and magnetic field detection. Since the telemetry encoder and electronic data system was never designed to survive radiation fluxes in excess of natural belt environment, it was expected that the operational lifetime in Explorer XV would be short--which indeed it was. After approximately 100 days this satellite ceased transmitting, although at the time of failure the P on N solar cells were providing about twice the required spacecraft power. Useful life came to an end after approximately 90 days when failure symptoms were observed in the telemetry encoder which exhibited malfunctions in the binary counters. It was never established why the rf carrier ceased with a surplus of power available.

Since the flight spare hardware from Explorer XV was earmarked for a second artificial belt mapping-satellite in the same orbit, it became our task to undertake a radiation hardening exercise to see if the life of the spacecraft electronics could be extended comparable with the life expectancy of P on N solar cells with 60 mil glass. Post-mortem radiation testing was conducted on the various subsystems to determine, if possible, the cause of failure since it was unlikely that the encoder caused transmission to cease. Subsystem testings for radiation damage was initiated for the first time at GSFC and was expeditiously and economically done using prototype spares. As a result of many tests, using gamma rays and/or 2 MEV electrons, only a few subsystems were found deficient and component changes were made in the telemetry encoder and several subcommutating networks. These investigations did not reveal any clues to transmission failure of Exp  r XV. Radiation hardening consisted of replacing grease filled PNP transistors and replacing NPN types with planar or with good mesa type transistors having known radiation tolerance. To instrument Explorer XXVI, changes were made only on a few dozen components representing not more than 10% of the total complement. This spacecraft was launched December 21, 1964, and is still operational and as of this writing has been exposed to radiation well in excess of $10^{14}$ electrons/cm$^2$ with energy above 0.5 MEV.

Present and future spacecraft electronic systems are now being designed with full consideration of the radiation environment to be expected in the proposed orbit of the spacecraft The flux mapping originally done on the artificial belt by Dr. Wilmot Hess of GSFC[1] and now updated and expanded by Dr. James I. Vette of the Aerospace Corp. has taken much of the guesswork out of the radiation hardening exercise. The system designer, equipped with an accurate picture of the expected radiation environment, is prepared to make decisions regarding part selection and shielding requirements to closer tolerances.

The IMP-D&E and F&G spacecrafts are examples of close tolerance design. The spacecraft PFM telemetry encoding system on both of these missions will contain mostly MOSFETs even though these devices are notoriously vulnerable to radiation damage. The choice to use the readily available P-channel enhancement type MOSFETs was made primarily to conserve power and secondly to reduce circuit complexity. IMP-D&E are to be magnetic field, plasma and energetic particles mapping spacecraft anchored in a lunar orbit approximately 1000 km above the surface of the moon. IMP-F&G is a similar spacecraft and is an improved version of the IMP-A, B, and C (Explorers XVIII, XXI, and XXVIII). IMP-F&G are to be launched in a highly elliptical earth orbit with an apogee of 196,000 km. Both missions require continuous monitoring of 8 or more scientific experiments each requiring digital-data storage. The digital-data is stored and commutated in the portion of the telemetry encoding system referred to as the digital-data-processor.[2] The entire encoder including the clock and data processor and A/C converter is designed using MOSFETs with a minimum of conventional transistors. By using MOSFETs the circuit parts count and power were not only reduced over conventional components but also the more compact construction permitted fabrication with fewer electronic cards and interconnectors. The basic building blocks used are a MOSFET monolithic-binary and a triple "nand" and "nor" gate. Discrete conventional transistors are used in all interface circuits in and out of the encoding system.

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[1] W. N. Hess, "The Bomb-Produced Radiation Belt," IEEE Transactions on Nuclear Science, Vol. NS-10, January 1963, No.1, p.8-11.

[2] H. D. White, "Considerations on the Design of PFM Telemetry Encoders," Proceedings of the 1962 National Telemetering Conference, Vol.1, Sec. 3-4.

For purposes of comparison the new IMPs parts count is compared with the earlier version of these spacecraft.

| S/C | PFM Encoding System Number of Bits of Storage | Number of Active Parts |
|---|---|---|
| IMP-A,B,C | 105 bits plus S/C clock | 1200 Transistors |
| IMP-D,E | 200 bits plus S/C clock | 747 MOS Packs (equivalent of 2000 transistors) |
| IMP-F,G | 421 bits plus S/C clock | 1437 MOS Packs (equivalent to 4000 transistors) |

The considerable savings in parts and power permit the inclusion of extra weight to the spacecraft in the form of shielding as required for the two missions.

Because of the vulnerability of MOSFETs to radiation damage, it is proposed that in addition to normal spacecraft shielding that 1 $gm/cm^2$ of package shielding will be added to the electronic cards containing the MOSFETs for the lunar IMP-D&E and 2 $gm/cm^2$ for the IMP-F&G. To determine that all MOSFET integrated blocks are uniform in their radiation damage properties, samples of the various manufactured lots are tested as received at GSFC in the $Co^{60}$ Gamma Cell. Many samples have been irradiated with 2 Mev electrons, gamma rays, and 22 Mev protons, and by direct comparison of the damage produced it is not difficult to establish damage equivalence. The gate threshold voltage is by far the parameter most subject to change as a function of irradiation and this damage is also a function of the magnitude of the gate-source-voltage (forward bias). This characteristic is demonstrated in Figure 1. These data were obtained from a single monolithic device which was successively irradiated with three different voltages between gate and source. Measurements were obtained with the sample removed from the source of radiation. Evidence of only small degradation in transconductance is evidenced by the relative uniformity of the three curves taken at different drain currents. In general all the devices tested showed less than 10% change in $g_m$ up to a dose of $10^6$ rads. In some cases there would be a tendency for a slight increase in $g_m$ before a decrease was evidenced.

Drain-source leakage current changed only a few nanoamps and gate leakage was not found to change at all with a dose of $10^6$ rads. The lower limit of the instrumentation used for these tests was only $10^{-9}$ amps.

The effects of gate voltage on two different devices are shown in Figure 2 ($V_{GS}$ = 20 V) and Figure 3 ($V_{GS}$ = 10 V) using $Co^{60}$ gamma rays. Figure 4 shows combined curves of three different devices with changes in gate-threshold voltage as a function of 2 Mev electron dose. Figure 5 is similar data obtained with 22 Mev protons. It should be noted that each data point shown on all curves in Figure 1 through Figure 5 are an average of three MOSFETs on a single monolithic block. Without exception all three tracked exceptionally close, (within a few percent). This uniformity of individual MOSFETs was consistant even when $V_{GT}$ experienced very drastic changes with dose. The monolithic construction may offer the solution for differential analog circuitry in a radiation environment.

MOSFET application in the IMP encoder systems, however, are digital and designed to tolerate several volt shift in $V_{GT}$. The most critical circuits such as the telemetry clock and A/D converter are buried deep in the electronic package to benefit from the shielding offered by other less important and less sensitive circuit modules. Enough shielding is added to the total electronic package to insure that the internal electron dose does not exceed $10^{11}$ electrons/cm$^2$/year or in the case of the lunar IMPs D&E not more than $10^{10}$ protons/cm$^2$ per year. There is always the possibility that solar activity during 1966 and 1967 could enhance the radiation environment to reduce the small margin of safety now estimated; however, up until spin balance prior to launch there will be the opportunity to evaluate the situation and add additional shielding, if required. Fortunately, the lunar IMP-D&E which has the greatest weight limitation has the greatest margin of safety in terms of expected dose.

Although no concentrated work is now underway at GSFC to determine the failure mechanism of P-channel MOSFETs with irradiation, occasionally we have the opportunity to investigate properties of the damaged units. For example, a number of devices have been annealed at 200°C to confirm the suspicion that the damage is not in the nature of bulk damage but instead must be related to a surface phenomenon. Future testing is planned to shed more light on this subject.

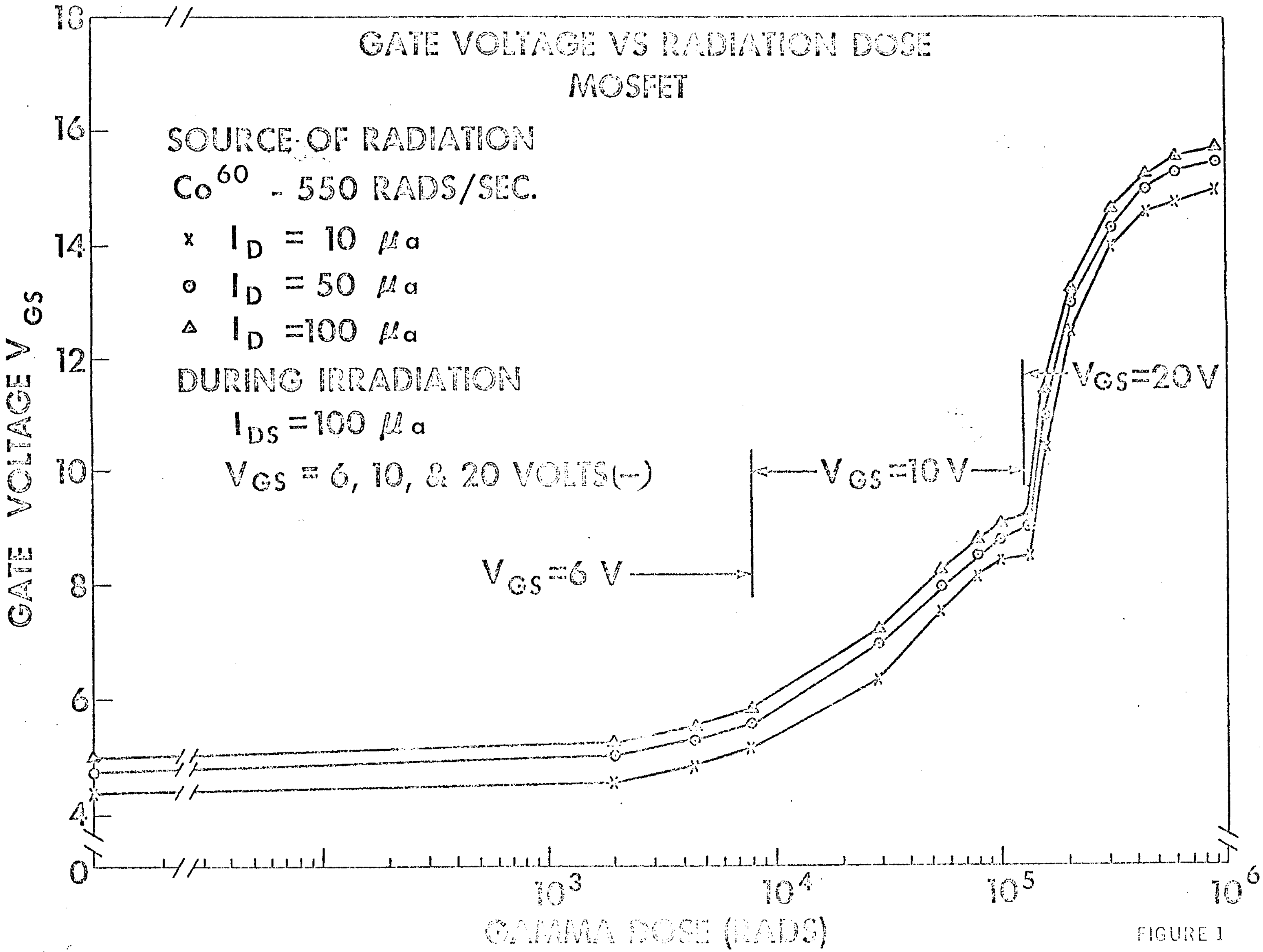
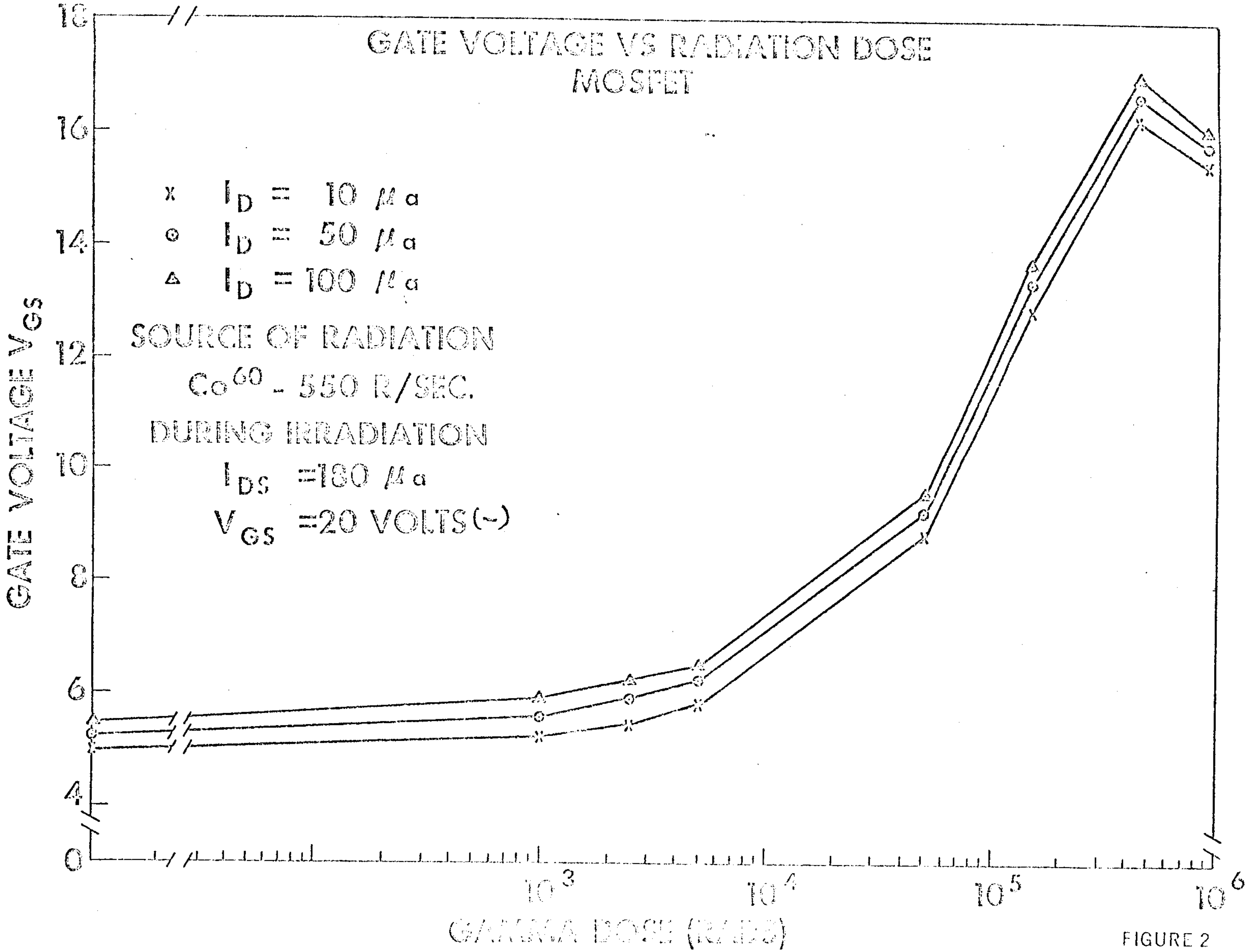
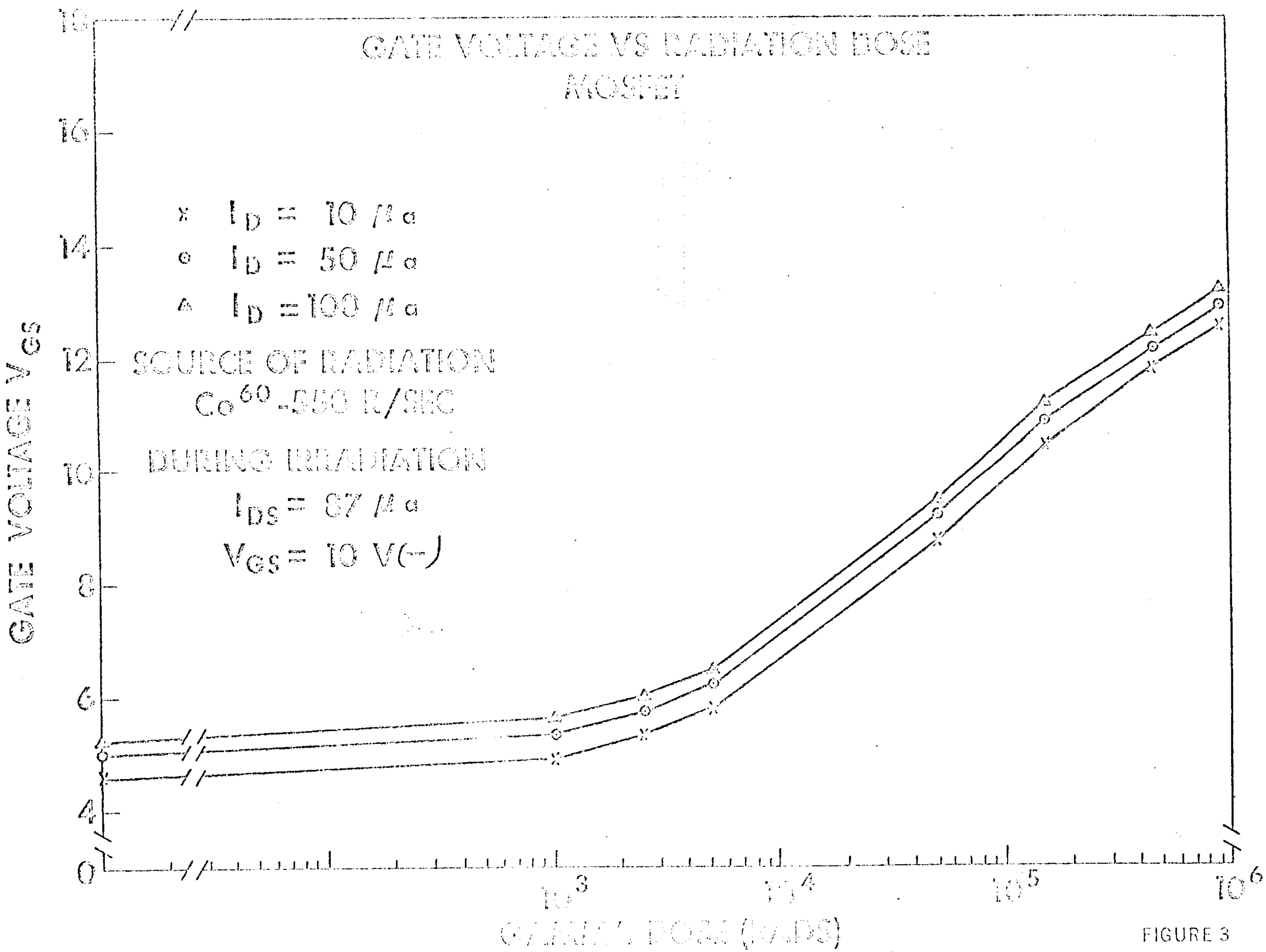

GATE VOLTAGE VS RADIATION DOSE
MOSFET
SOURCE OF RADIATION
Co60 - 550 RADS/SEC.
x ID = 10 μa
o ID = 50 μa
Δ ID =100 μa
DURING IRRADIATION
IDS =100 μa
VGS = 6, 10, & 20 VOLTS(-)
VGS=6 V
VGS=10 V
VGS=20 V
GATE VOLTAGE VGS
GAMMA DOSE (RADS)
18
16
14
12
10
8
6
4
0
10^3
10^4
10^5
10^6

FIGURE 1



GATE VOLTAGE VS RADIATION DOSE
MOSFET
x I D = 10 μa
⊙ I D = 50 μa
Δ I D = 100 μa
SOURCE OF RADIATION
Co 60 - 550 R/SEC.
DURING IRRADIATION
I DS =180 μa
V GS =20 VOLTS(~)
GATE VOLTAGE V GS
18
16
14
12
10
8
6
4
0
10 3
10 4
10 5
10 6
GAMMA DOSE (RADS)


FIGURE 2



GATE VOLTAGE VS RADIATION DOSE
MOSFET
x $I_D$ = 10 μa
⊙ $I_D$ = 50 μa
Δ $I_D$ = 100 μa
SOURCE OF RADIATION
$Co^{60}$ -550 R/SEC
DURING IRRADIATION
$I_{DS}$ = 87 μa
$V_{GS}$ = 10 V(–)
GATE VOLTAGE $V_{GS}$
0
4
6
8
10
12
14
16
18
$10^3$
$10^4$
$10^5$
$10^6$
GAMMA DOSE (RADS)


FIGURE 3

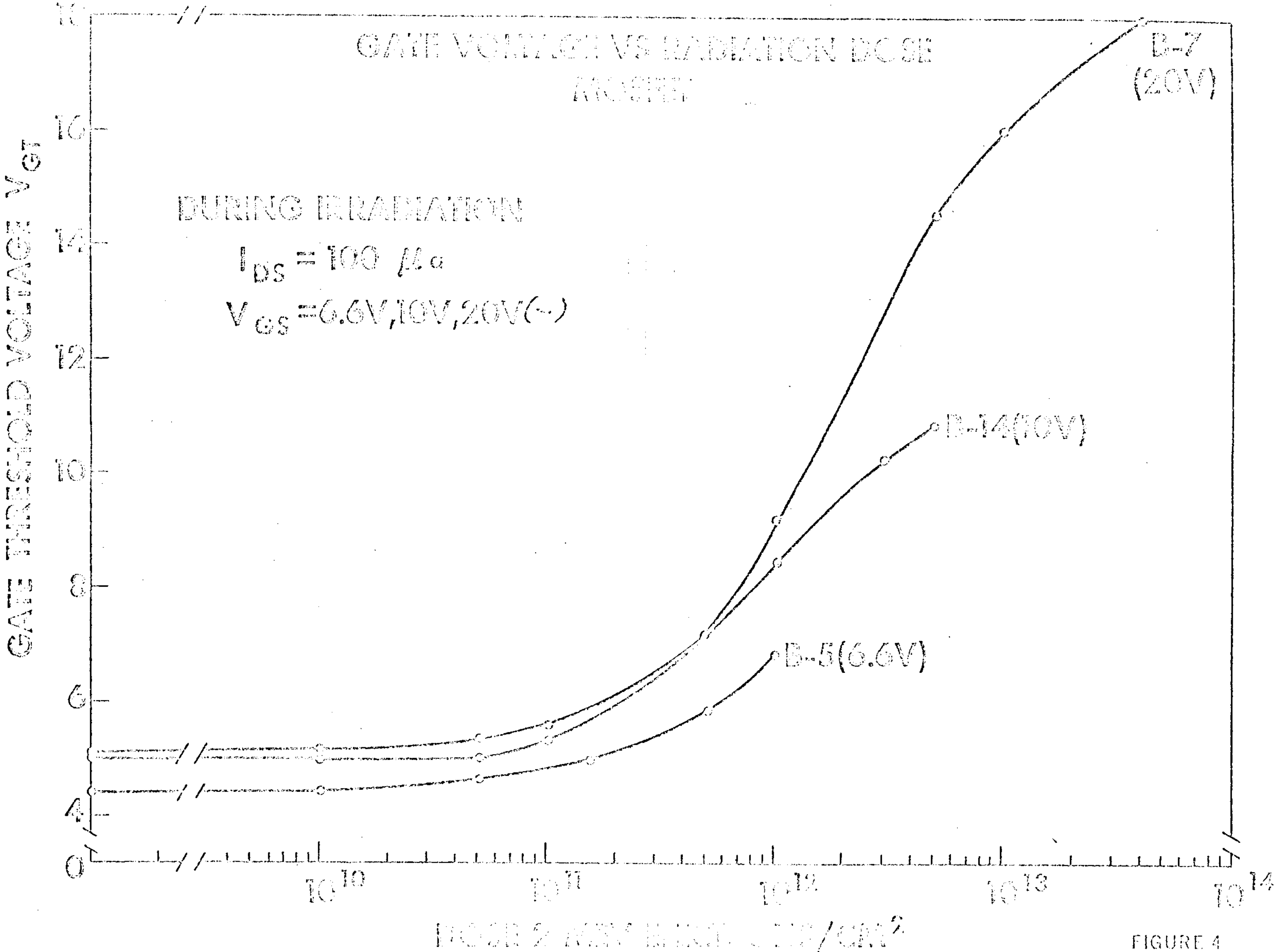
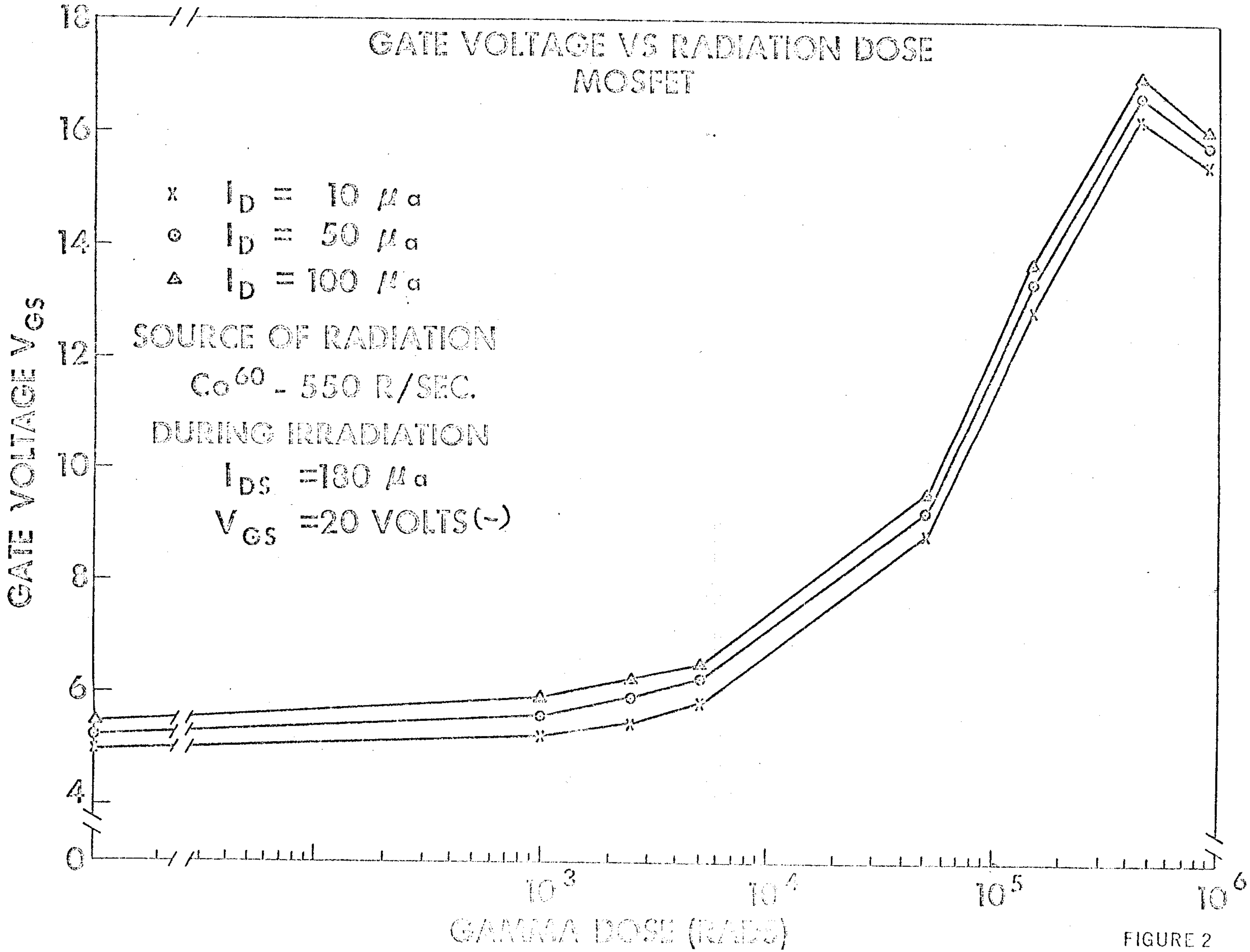

GATE VOLTAGE VS RADIATION DOSE
MOSFET
DURING IRRADIATION
$I_{DS} = 100\ \mu a$
$V_{GS} = 6.6V, 10V, 20V(-)$
B-7
(20V)
B-14(10V)
B-5(6.6V)
GATE THRESHOLD VOLTAGE $V_{GT}$
0
4
6
8
10
12
14
16
$10^{10}$
$10^{11}$
$10^{12}$
$10^{13}$
$10^{14}$

FIGURE 4



GATE VOLTAGE VS RADIATION DOSE
MOSFET
x $I_D$ = 10 μa
⊙ $I_D$ = 50 μa
△ $I_D$ = 100 μa
SOURCE OF RADIATION
$Co^{60}$ - 550 R/SEC.
DURING IRRADIATION
$I_{DS}$ =180 μa
$V_{GS}$ =20 VOLTS(-)
GATE VOLTAGE $V_{GS}$
0
4
6
8
10
12
14
16
18
$10^3$
$10^4$
$10^5$
$10^6$
GAMMA DOSE (RADS)


FIGURE 2

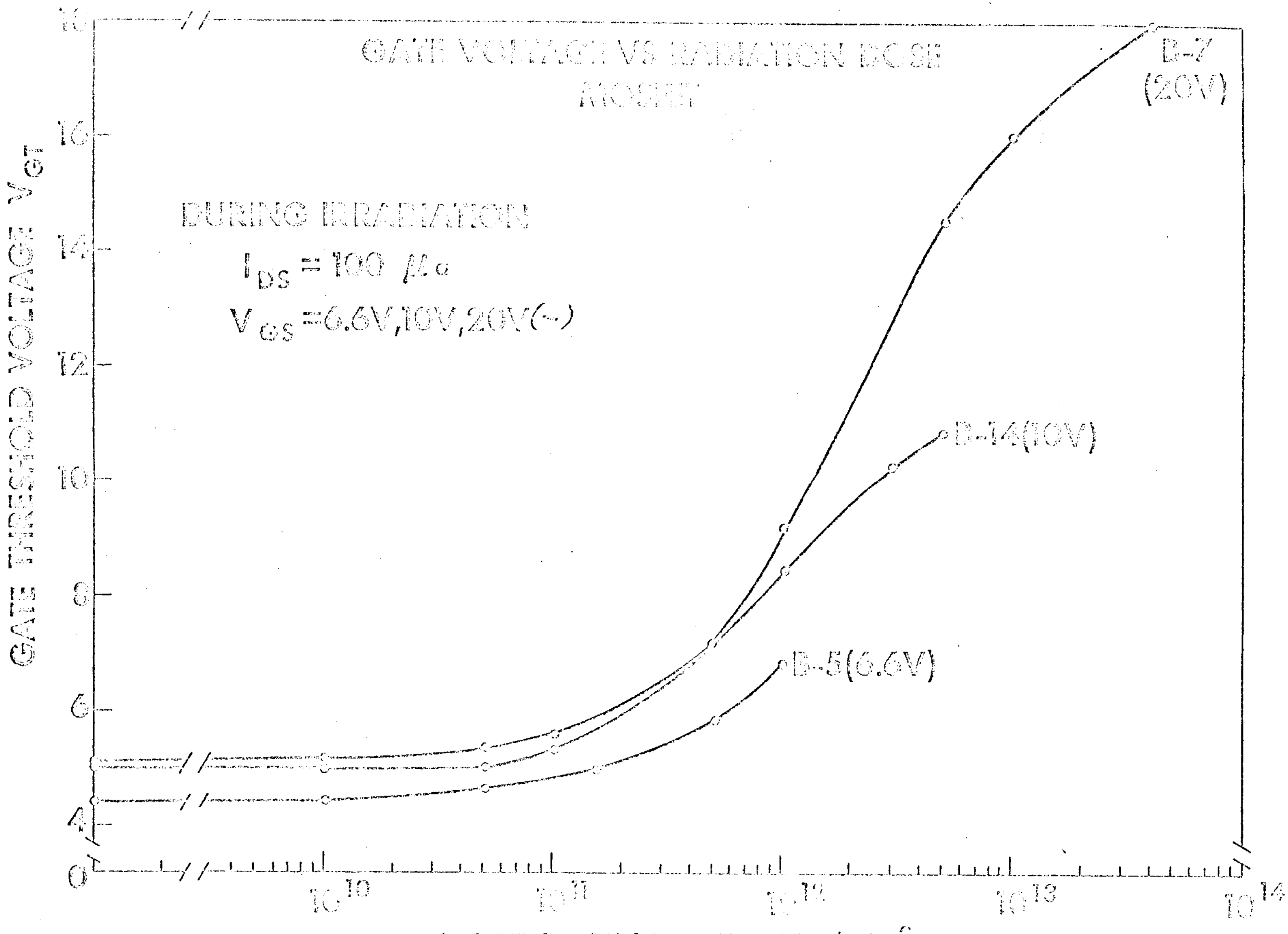

GATE VOLTAGE VS RADIATION DOSE
MOSFET
DURING IRRADIATION
$I_{DS}$ = 100 μa
$V_{GS}$ =6.6V,10V,20V(-)
B-7 (20V)
B-14(10V)
B-5(6.6V)
GATE THRESHOLD VOLTAGE $V_{GT}$
0
4
6
8
10
12
14
16
$10^{10}$
$10^{11}$
$10^{12}$
$10^{13}$
$10^{14}$

FIGURE 4

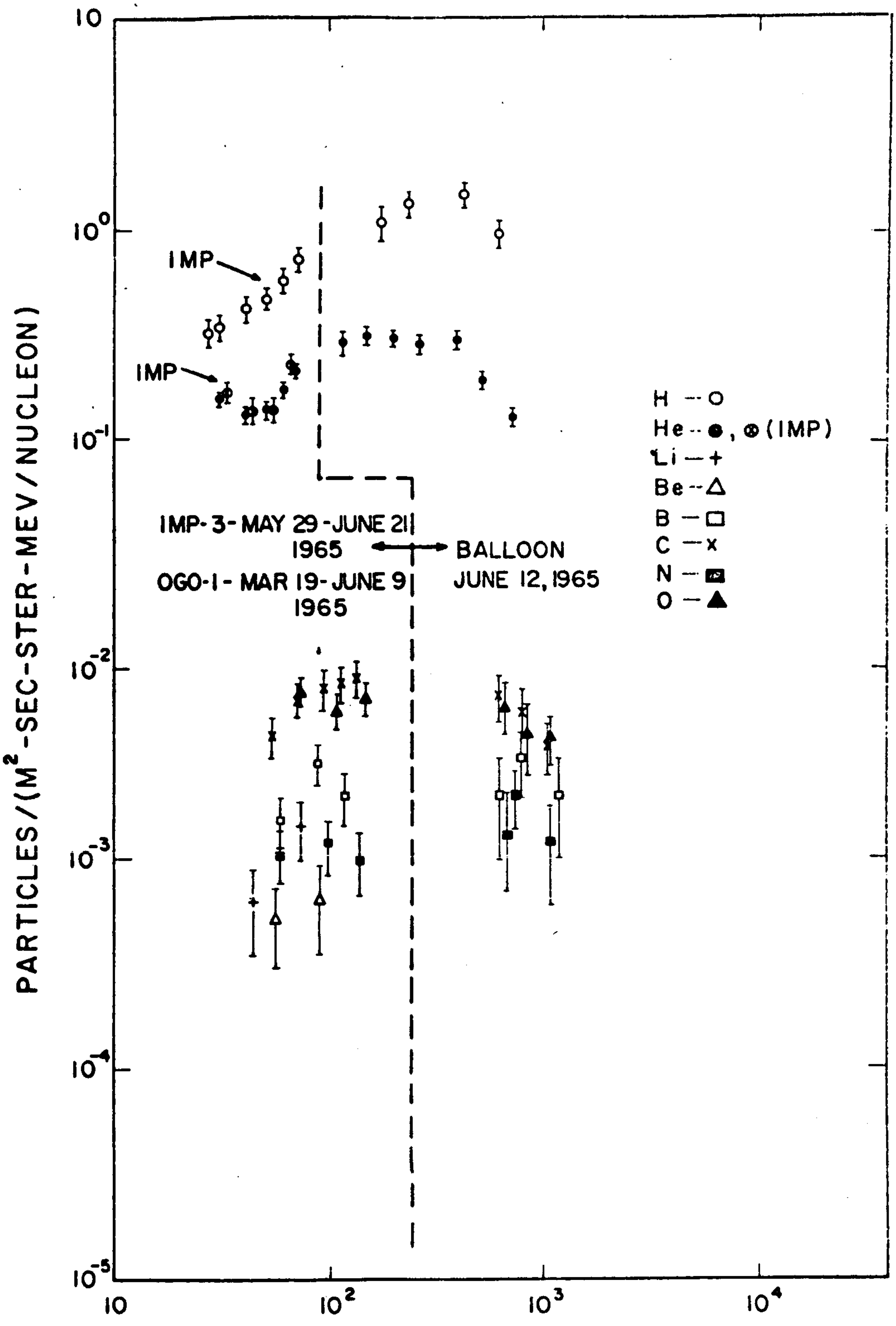



Figure 7. The composite energy spectra of nuclei from protons to oxygen from 25 Mev/nucleon to 1 Bev/nucleon. The proton spectrum is from IMP III.